OPTIMIZING INITIAL ATTACK EFFECTIVENESS BY USING PERFORMANCE MEASURES

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ABSTRACT

Increased scrutiny of federally funded programs combined with changes in fire management has created a demand for a new fire program analysis model. There is now a need for a model that displays tradeoffs between initial attack effectiveness and alternative funding levels. The model is formulated as an integer linear program that operates in a performance based, cost-effectiveness analysis (CEA) environment. Using the performance measure of weighted area protected (WAP), the model employs a non-monetized approach to interagency fire planning. The model optimizes the initial attack deployment for a user-defined set of fires that a manager would like to be prepared for across alternative budget levels. The paper shows how an integer programming formulation can use optimal deployment to address the annual fire program. It is also shown, for the first time how simultaneous ignitions can be incorporated into an optimization approach. This compact and robust model can provide the basis for a wider scale formulation with the potential to measure an organization's performance and promote a higher level of accountability and efficiency in fire programs.

INTRODUCTION

Estimating the preparedness organization for an upcoming wildfire season on public lands is a complex process. Federal land management agencies expend considerable effort to estimate the budget and to decide upon the resources that will be needed to protect public lands from wildfire each year. In preparedness planning, a fire manager's decisions often include the type and number of firefighting resources to have available. The difficulty of determining the number of resources is often compounded by the occurrence of simultaneous ignitions and having to plan for the possibility of receiving alternative appropriation levels. A suitable analysis of the tradeoffs of all of the possible combinations of appropriation levels, resources, and uses, requires a sound analytic system and a definitive measure of performance.

Many approaches have been suggested to assist decision makers in analyzing parts of the preparedness problem. Approaches employing optimization have their roots in World War II and the birth of operations research. Much of the optimization literature extends Parks (1964) who designed a deterministic model to minimize the cost of suppression plus damages to find an optimal constant workforce. See Parlar and Vickson (1982), Parlar (1983), Aneja and Parlar (1984) for models that extend the Parks formulation. Boychuk and Martell (1988) also evaluated seasonal forest fire fighter requirements utilizing the least cost plus loss framework by using Markov chains. Recently, Donovan and Rideout (2003) used an integer linear programming model to optimize a firefighting resource allocation to a single fire using a cost plus net value change framework.

Despite the difference in optimization approaches, most previous models have relied heavily on derivatives of the cost plus loss theory first applied to wildfire in the early 20th century (Sparhawk 1925). The cost plus loss framework requires monetization of the damages caused by wildfires. As a fire advances across a landscape it can affect a

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myriad of natural resources, each posing its own challenge for accurate valuation. The valuation of fire damage continues to be an extremely difficult and costly task (Cleaves 1985; Pyne and others 1996).

Non-monetized approaches have also been used in a few fire management applications. For example, Kourtz and O'Regan (1968) used a cost effectiveness analysis (CEA) to assess fire detection systems, Nautiyal and Doan (1974) used iso-dissatisfaction curves to assess trading planned cut for wildfire protection expenditures, Omi and others (1981) used a damage reduction index to optimize fuel treatments, and Mees and Strauss (1992) used a utility measure of the relative importance of holding different constructed fireline segments to evaluate strategies for the tactical deployment of resources to a single large fire. Our research has been enriched by these previous studies as we have developed an optimization model in a non-monetized system.

Here we provide the first non-monetized application of an optimization model applied to preparedness planning. This approach shows how a strategic fire management planning effort can utilize integer linear programming to organize and optimize the initial attack response, in a CEA framework. The output of the model gives the planner an optimal list of resources to have available for an entire season across a range of possible budget appropriations. The model accounts for simultaneous ignitions, which are important planning elements that have not previously been considered in an optimization model.

DEVELOPING THE MODEL

Our approach demonstrates how a performance based optimization model can inform strategic planning decisions. For example, the model can provide information to aid with the development of a menu of initial attack firefighting resources that would be available for the fire season while considering both single and simultaneous fires. This strategic scope is in contrast to tactical or real-time decision-making such as the deployment of specific resources to a specific fire event. Because we optimize initial attack performance, as opposed to extended attack or large fires, only local resources affecting the planning unit's budget allocation are included in the model.

We use a deterministic integer linear programming (ILP) optimization approach to model the initial attack planning problem for several reasons. First, strategic planning involves decisions that are often integer or binary. These decisions include the number, location, and type of resources to have available for deployment to a set of fires. Second, an ILP allows for the evaluation of thousands of decisions in a compact and flexible formulation. Our optimization model employs a performance-based CEA to display the tradeoffs between funding levels and initial attack performance. Cost effectiveness analysis helps decision makers allocate limited resources efficiently when performance measures are used in lieu of monetized benefit estimates (Robinson and others 1995; Osborne and Plastrik 2000). The results of a CEA are often displayed by forming a frontier as in figure 1, where costs are compared with effectiveness. While all points on the interior of the frontier are possible, they are technically inferior to points that comprise the frontier. For any interior point, there is at least one point on the frontier that can be shown to be preferable. Optimization enables the analyst to focus on solutions or points that define the frontier.

To compare the effectiveness of different initial attack organizations, we provide a performance measure defined as the weighted area protected (WAP). A WAP is a geographical area (for example, acre or hectare) assigned a proportional numerical weight representing the importance of protecting that area relative to another area from damaging wildfires. The WAP combines both qualitative and quantitative assessments of damage caused unwanted wildfires. Not all fires are created equal and the WAP captures the importance of protecting our natural treasures in a way that dollars values could not. Tradeoffs are clear to see and are directly related to performance on the ground. Defining WAP as a performance measure will allow the model to weigh the possibility of using scarce resources to contain more important fires while letting less important fires escape. Using a frontier estimated from the collection of a program's analyses, the overall effectiveness of the initial attack organizations can be displayed and analyzed as in figure 1.

The model requires an input set of fires that reflect the expected workload of a future fire season. Initially, the model needs predetermined initial response analysis period. This time can take on any value and each time step does not have to be constant allowing for a flexible analysis. Each fire is defined by an initial reporting size at time zero and its total cumulative perimeter and area burned for each time step in the analysis period. The fire's perimeter is directly related to cost through resource production rates and the fire's burned area is directly related to performance through WAP. Other fire behavior characteristics such as flame length and fire intensity can be reflected in the firefighting resources' ability to construct fireline. This allows managers to incorporate tactical firefighting standards, such as a fire with flame lengths of four to eight feet can

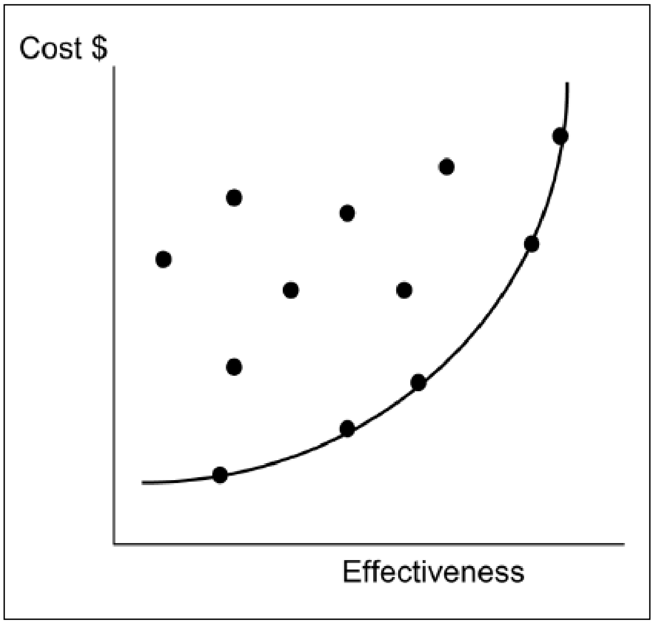

Figure 1—Generic cost-effectiveness frontier

be too intense for a direct attack with hand tools, but bulldozers, engines, and aerial drops can be effective (BLM Standards Chapter 9 2003). We use the free burning fire containment rule from previous deployment models (for example, USDA Forest Service 1991; Donovan and Rideout 2003) that states a fire is contained when the total fireline produced by firefighting resources is greater than the free burning fire perimeter. A fire is defined as having escaped initial suppression efforts if it cannot be contained in the initial attack time period because of either a lack of funds or inadequate fireline production.

The attributes of the firefighting resources constitute the main set of inputs to the optimization routine. The model requires a list of resources to choose from in order to maximize the WAP. This list includes all of the resources that are potentially affected by a planning unit's budget. Each resource is defined by a total fireline production and by its fixed and variable cost. Fireline production is input to the model as cumulative values for every time step of each fire. An advantage of this integer time step format is that the production rate does not have to be constant or linear and can reflect fatigue and other disruptions in the production such as water refills and refueling. Arrival and other travel times are also reflected in these production values. Resources produce zero chains of fireline during travel periods. The model uses the production information along with costs to solve for the optimal deployment.

The costs of initial response resources are important considerations in estimating the optimal deployment. While previous approaches included cost information, costs did not directly affect resource deployment. Our model relies upon fixed and variable costs that are directly input to aid with the management of optimal deployment (Donovan and Rideout 2003). The fixed cost is modeled as a one-time charge that is incurred only if the resource is deployed to any fire during the season. Each resource's variable cost is modeled as an hourly cost that reflects its operating costs on each fire, including maintenance, fuel, regular hourly wages, overtime and hazard pay.

Including simultaneous ignitions in the optimization model adds depth and advancement to the analysis. To model simultaneous ignitions we force certain resources to choose to fight a maximum of one of the simultaneous ignitions. We assume that once a resource is deployed to a fire, it is not released when containment is achieved for another deployment.

The following is the mathematical representation of the model:

Maximize WAP

$$WAP_o - \sum_{i=1}^{I} \sum_{d=0}^{D_e} (W_{id} * f_{id} * A_{id}) \qquad (1)$$

Subject to:

$$\sum_{d=1}^{D} x_{ird} \leq u_r \qquad \forall i,r \qquad (2)$$

$$\sum_{d=0}^{D_e} f_{id} = 1 \qquad \forall i \qquad (3)$$

$$\sum_{r=1}^{R} \sum_{d=1}^{D} (x_{ird} * L_{ird}) \geq \sum_{d=0}^{D} f_{id} * P_{id} \qquad \forall i \qquad (4)$$

$$\sum_{d=0}^{D} d * f_{id} \geq \sum_{d=1}^{D} d * x_{ird} \qquad \forall i,r \qquad (5)$$

$$\sum_{i=1}^{I} \sum_{r=1}^{R} \sum_{d=1}^{D} (x_{ird} * H_{rd}) + \sum_{r=1}^{R} u_r * F_r \leq TC \qquad (6)$$

$$\sum_{r \in S_n} \sum_{d=1}^{D} x_{ird} \leq u_r \qquad \forall n,r \in R_S \qquad (7)$$

Decision Variables

x_{ird} = Binary(0,1) = 1 if resource (r) is used for (d) time periods on fire (i).
= 0 if resource (r) is not used on fire (i) for (d) time periods.

f_{id} = Binary (0,1) = 1 if fire (i) burns for (d) time periods.
= 0 if fire (i) does not burn for (d) time periods.

u_r = Binary(0,1) = 1 if resource (r) is deployed to any fire for any duration.
= 0 if resource (r) is never used.

Parameters

I = set of all fires indexed by i.
R = set of all firefighting resources indexed by r.
D = resource deployment and contained fire duration indexed by d.
D_e = escaped fire duration. De is defined as D+1.
S_n= (n)th set of simultaneous ignitions.
$S_n \subseteq I$.
R_s = set of firefighting resources that are restricted to fight at most one of the fires that ignite simultaneously.
$R_s \subseteq R$.
F_r = fixed cost for resource (r).
H_{rd} = total hourly cost accrued for resource (r) for (d) time periods.
L_{ird} = total (cumulative) fireline produced by resource (r) for (d) time periods during fire (i).
W_{id} = relative weight for the area burned by fire (i) after (d) time periods.
P_{id} = total fire perimeter of the burned area for fire (i) after (d) time periods.
A_{id} = total area burned by fire (i) after (d) time periods. Calculated from P_{id}.
TC = total cost of initial attack input to the model.
WAP_o = total weighted area of the fire planning unit.

The objective function (1) maximizes effectiveness defined as the weighted area protected for a given budget. Equation (2) limits a resource to at most one deployment per fire. For example, a firefighting resource cannot be deployed for two time periods and four time periods to the same fire. The equalities in (3) force each fire to have exactly one burn duration. Equations (4) are the containment constraints. For each contained fire, the total amount of fireline produced by all resources must be greater than or equal to the fire's burn perimeter. Equations (5) force each fire to burn at least as long as the longest duration of any resource deployed to that fire. For example, if on a given fire there were two resources used, one for three time periods and the other for six time periods, the fire would burn for six time periods. Inequality (6) is the budget constraint. The total cost of all resources deployed to all fires, both hourly and fixed, must be less than or equal to the total cost denoted as TC. Equations (7) are used for fires that are modeled as simultaneous ignitions. Fires in these groups compete for firefighting resources. We assume that a resource can only be deployed to one fire in each group of simultaneous ignitions.

CONCLUSION

Our formulation provides an approach to performance based initial attack planning that incorporates the tenets of CEA in an optimization model. The performance measure of WAP shows how a non-monetized performance based system could be applied while addressing key elements of preparedness planning. While this model expanded previous work to optimize simultaneous ignitions, future efforts could continue to expand the scope of analysis. For example, one could change the deterministic model to incorporate stochastic elements, such as a range of likely fire occurrences. Other possible scope extensions could include linear or piecewise linear approaches to reduce the solution times.

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